

# Integrating economic input–output life cycle assessment with risk assessment for a screening-level analysis

Heather E. Wright • Qiong Zhang • James R. Mihelcic

Received: 13 June 2007 / Accepted: 28 January 2008 / Published online: 29 April 2008  
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## Abstract

**Goal, Scope, and Background** The paper describes the integration of the economic input–output life cycle assessment (EIO-LCA) model and the environmental fate and transport model (CHEMGL) with a risk assessment tool. Utilizing the EIO-LCA, instead of a traditional LCA, enables a rapid, screening-level analysis of an emerging chemical of concern, decabromodiphenyl ether (DecaBDE). The risk assessment in this study is evaluated based on the mass of chemical released, estimated concentrations, exposure, and chemical toxicity.

**Methods** The relative risk from ten economic sectors identified within the EIO-LCA model, 55 chemicals utilized in those sectors and DecaBDE along with four potential DecaBDE breakdown products, were evaluated for the life cycle stages and exposure pathways. The relative risk (expressed as toluene equivalents) of the different chemicals, sectors, and life cycle stages were compared to assess those representing the greatest overall relative risks to humans (via inhalation and ingestion) and fish.

**Results** The greatest overall risk to human health resulted from the manufacturing and production stages. For fish, the manufacturing stage represented virtually all of the risk. Of the 56 chemicals evaluated, DecaBDE represented the majority of the total risk to humans. However, DecaBDE posed the least risk compared to its potential breakdown products.

**Discussion** The risk to humans from ingestion, which represented the greatest risk, from the production, manufacturing, and consumption stages can be controlled and reduced through various safety precautions in the workplace. Additionally, the increasing concentration of DecaBDE in anaerobic compartments represents a threat to humans and fish via the higher risk DecaBDE breakdown products.

**Conclusions** Overall, the manufacturing and production life cycle stages pose the greatest risk to humans and fish. The sediment compartment received the highest DecaBDE concentration for the production, manufacturing, and consumption stages. This case study demonstrates that the integrated EIO-LCA with risk assessment is suitable for screening-level analysis of emerging chemicals due to rapid life cycle inventory analysis.

**Recommendations** The production and manufacturing stages allow for greater industry control and government regulation, compared to the consumption stage, because there are fewer point sources. This integrated life cycle methodology may allow chemical designers to evaluate each stage and assess areas where risks can be minimized.

**Keywords** Decabromodiphenyl ether • Economic input–output LCA • Emerging chemical of concern • Flame retardants • Risk assessment

Responsible editor: Sangwon Suh

H. E. Wright • Q. Zhang (✉) • J. R. Mihelcic  
Department of Civil and Environmental Engineering,  
Sustainable Futures Institute, Michigan Technological University,  
1400 Townsend Drive,  
Houghton, MI 49931, USA  
e-mail: qiong@mtu.edu

## 1 Introduction

Traditional life cycle assessment (LCA) provides a holistic and systematic perspective; however, it is data intensive and time consuming, requires comprehensive analysis, and is expensive to conduct (Curran 1996; Deanna and Fullerton 1994). To respond to these challenges, researchers at

Carnegie Mellon University (CMU) created the economic input–output life cycle assessment (EIO-LCA) model which estimates material and energy inputs and environmental outputs resulting from economic sector production or service provision (CMU Green Design Institute 2006). The EIO-LCA model allows for rapid analysis, utilizes publicly available data, is inexpensive, and is appropriate for screening-level analysis (Bilec et al. 2006). Although LCA provides a means to identify and evaluate inputs and the resulting outputs, there has been little progress in translating these environmental outputs into estimates of impacts to human health and the environment (Matthews et al. 2002). Risk assessment provides a means to quantify health and environmental impacts of a product or process, which allows the potential health effects of the outputs to be estimated. These two types of assessment are closely connected and there have been efforts to incorporate or address risk assessment within a traditional LCA approach (Guinée and Heijungs 1993; Pant et al. 2004; Saouter et al. 2001; Saouter et al. 2002; Jolliet et al. 2006; Larsen and Hauschild 2007); however, this has not been infused into EIO-LCA.

Previous EIO-LCA (Hawkins et al. 2007; Bilec et al. 2006; Chen et al. 2001; Swarr et al. 2004) case studies evaluated environmental impact from chemical releases based on the mass of chemical released. Environmental fate and transport models and toxicity information have not been integrated in these studies to address the relative risks of chemicals. In this case study, a unique approach of integrating EIO-LCA with a risk assessment tool is applied for screen-level analysis to examine the relative risk posed during each life cycle stage of an emerging chemical of concern, a brominated flame retardant (BFR)—decabromodiphenyl ether (DecaBDE). Emerging chemicals of concern are chemicals relatively new to commerce that are being found to have health and environmental risks such as damaging genetic material, interfering with hormonal systems, persisting in the environment, and bioaccumulating in living organisms. The proposed approach is very suitable for emerging chemicals because it is difficult to compile life cycle inventory data for such chemicals using traditional LCA approach.

## 2 Chemical of concern

DecaBDE is a widely used flame retardant commonly added to plastics, polyurethane foams, and textiles. Fire safety standards require the end products (e.g., electronics, computers, carpets, and upholstery) to contain flame retardants that help delay the onset and spread of fire. DecaBDE is the dominant congener (97–99%) in the commercial mixture, which is in the class of polybromi-

nated diphenyl ethers (PBDEs; Butt et al. 2003). DecaBDE is used in 80% of PBDE applications, and the concentration in products ranges from 10–15%; however, its use remains unregulated in the US (HRC 2004).

An additive process is used to incorporate DecaBDE into the materials. This results in the chemical slowly volatilizing into the environment during the product's lifetime (Butt et al. 2003). PBDEs have very similar structures to polychlorinated biphenyls, are persistent organic pollutants that do not degrade quickly in the environment, and may be absorbed by humans and wildlife (HRC 2004). Hites (2004) documents the exponential increase in PBDE concentrations in humans and wildlife, which have doubling times of 3 to 7 years. Bioaccumulation of DecaBDE appears to be low; however, the critical issue is that it can degrade into lower brominated diphenyl ether congeners (Hexa-, Hepta-, Octa-, and NonaBDE) that have shown higher bioaccumulation (Janssen 2005). DecaBDE is degradable under anaerobic conditions, in the presence of UV and natural light, and via metabolic processes in animals and microorganisms (Illinois EPA 2006). The increasing quantities of DecaBDE in anaerobic compartments (soil and sediment) could have serious consequences for the environment and human health (Gerecke et al. 2005).

## 3 Environmental fate and transport model development

### 3.1 National CHEMGL model

The environmental multimedia compartmental model, CHEMGL, was developed to predict the concentration of a chemical as a function of time for a given emission rate in the Great Lakes Region of North America (Zhang et al. 2003). A national US version of CHEMGL was developed so that it could be linked with the EIO-LCA software, which is based on national economic and toxic release inventory data in the US. CHEMGL considers ten major well-mixed compartments (i.e., stratosphere, troposphere, air boundary layer, surface water, sediment, surface soil, vadose soil, plant foliage, root zone, ground water) and accounts for diffusive and non-diffusive mass transfer. The CHEMGL model description (including figure of compartments and fate mechanisms), development, and environmental properties can be found in Zhang et al. (2003).

For the national model, the continental US was divided into nine regions based on climatic and geographic data. The regional specific parameters, 45 of 84 parameters, were identified, and values for those parameters were compiled for the regions (Wright 2007). For parameters available on a state-by-state basis (e.g., precipitation), individual state values were averaged to obtain regional values. The remaining parameters were determined on a regional basis

**Table 1** DecaBDE input emission rates, measured and predicted national CHEMGL model concentrations

Compartment	CHEMGL Input (kg·day <sup>-1</sup> )	CHEMGL predictions(ng·m <sup>-3</sup> )	Measured Concentration (ng·m <sup>-3</sup> )	Source
Air boundary layer	7.1 <sup>a</sup>	1.5e-03	1.4e-02–3.5e-04 <sup>b</sup>	BFRIP2002, Hites 2004, Janssen 2005
Surface water	7.1 <sup>a</sup>	1.8e+02	1.3e+02–3.8e+03	Zhu and Hites, 2005
Surface soil	7.1 <sup>a</sup>	2.5e+04	2.0e+07–3.7e+07 <sup>c</sup>	Janssen 2005
Sediment	0	2.7e+06	2.0e+07	Hites 2004

<sup>a</sup> Assuming total amount of DecaBDE accumulated in US for 10 years of consumption of 24,000 tons/year and a world distribution of 27% for DecaBDE

<sup>b</sup> Ambient air

<sup>c</sup> Measured at production facility

(e.g., dry deposition). The values from the nine regions were, then, averaged to obtain national parameter values and two methods were employed: (1) parameters independent of basin area (land plus water area) were calculated using a straight average of the nine regional values and (2) parameters dependent on basin area were estimated using a weighting factor—the ratio of a regional basin area to the total national basin area. The regional parameter values were multiplied by the weighting factor and then summed to obtain national parameter values.

### 3.2 Model validation for flame retardant chemical of concern

Although the regional CHEMGL model was verified (Zhang et al. 2003), the capability of the national CHEMGL model to predict the fate of chemicals in real environmental systems required validation. In order to validate the national model, the predicted compartment concentrations from CHEMGL were compared to measured data in the US. The model predicted the concentration of DecaBDE in all compartments for a 10-year period. The emission rate of DecaBDE to the air boundary layer, surface water, and surface soil compartments was estimated following a method used by the Danish Environmental Protection Agency (EPA; Lassen et al. 1999). Additional input data and emission rate calculations can be found in Wright (2007).

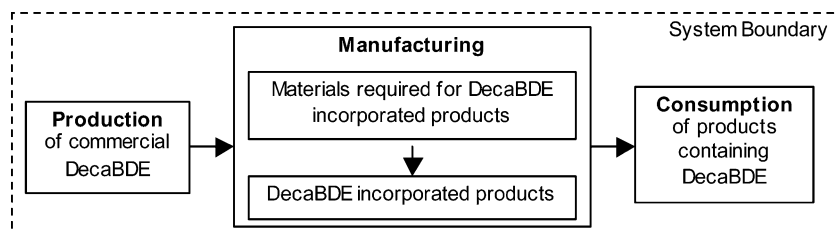
Limited data was available in the literature for background environmental concentrations of DecaBDE, which is highly dependent on the sampling location. No data was available for the following compartments: troposphere,

stratosphere, vadose soil, ground water, plant foliage, and root zone. Therefore, the predicted CHEMGL concentration output values for these compartments could not be verified or rejected and are not listed in Table 1. The predicted concentrations in the air boundary layer, surface water, and sediment compartments agree within one order of magnitude with reported concentrations and are considered to be acceptable for screening purposes. Average surface soil measurements were not available in the literature; however, measured concentrations of DecaBDE were reported from a production facility. These site-specific values are significantly greater than the average surface soil concentrations because they are measured at contaminated sites. As a result, the predicted surface soil concentrations from CHEMGL are less than the measured concentrations but fall within three orders of magnitude of the measured values. It was concluded that the national CHEMGL model is satisfactory to estimate chemical concentrations in environmental compartments for screening-level risk assessment.

## 4 Scope of the study

To streamline this analysis, the scope of the study includes the production of commercial DecaBDE, the manufacturing of DecaBDE incorporated products that includes premanufacturing of materials required for those products and the consumption of those products (Fig. 1). Due to the difficulty of recycling flame retarded materials, products containing BFRs are typically landfilled (Lassen et al. 1999). DecaBDE is vulnerable to photolytic debromination

**Fig. 1** System boundary of EIO-LCA case study



and if exposed to sunlight in landfills, photolysis could cause the transformation to lower brominated PBDE congeners. As discussed before, if these lower brominated PBDE congeners DecaBDE leach from the landfill, it will have serious consequences for the environment and human health. However, there have been very few studies on the fate of BRFs in landfills and no evidence of DecaBDE present in landfill leachate (Osako et al. 2004; Kim et al. 2006). This is likely due to the high hydrophobicity of DecaBDE, which tends to cause the compound to bind to organic carbon found in landfilled solid waste and prevents it from easily leaching out (Kim et al. 2006). Therefore, it is assumed that there is no emission of DecaBDE to the environmental compartments from landfilled products, and the end of life stage was not included in the system boundary. Additionally, the transportation stage is ignored in the study because it is assumed that the DecaBDE released from products during this stage is negligible. The main concern of DecaBDE is the impact to human health and ecosystem. Therefore, the relative risk to human health and fish are adopted as impact categories.

## 5 Methodology

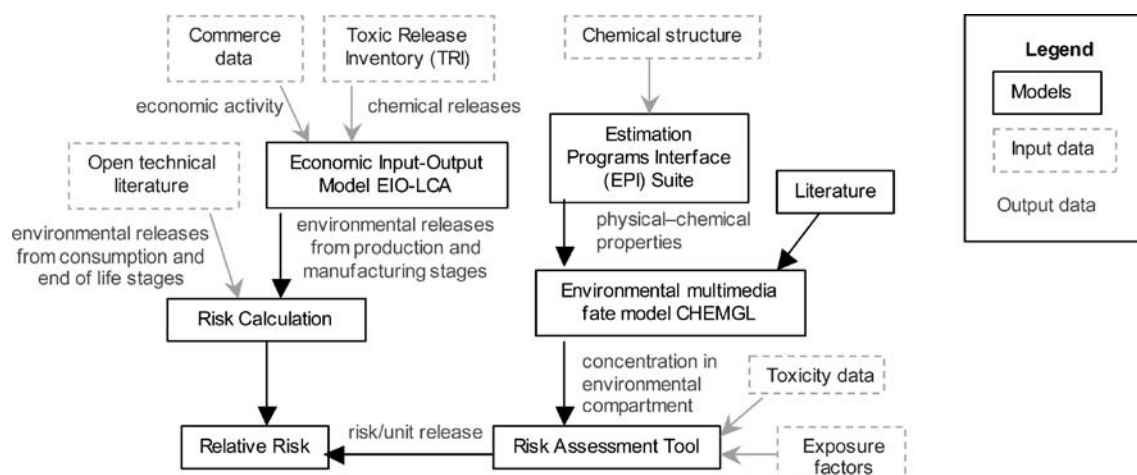
The methodology used to integrate the EIO-LCA with risk assessment for an emerging chemical is shown in Fig. 2. The environmental model requires the input of physical–chemical property data; however, much of this data for emerging chemicals was not available from the literature and had to be estimated from the chemical structure using the US EPA’s Estimation Programs Interface (EPI) Suite. Using the CHEMGL model, the chemical concentrations in the environmental compartments, as defined by the model,

were estimated and input into a risk assessment tool. The risk assessment tool is a spreadsheet developed by the authors that calculates indicators in units of toluene equivalence using chemical concentration and toxicity as inputs. The concept of toluene equivalence was originally proposed by Guinée and Heijungs (1993) and applied by other researchers (Hertwich et al. 2000) which compare the risk potential of a chemical to the reference chemical—toluene—with respect to unit release. The environmental releases were estimated based on information obtained from open technical literature and the EIO-LCA model. Finally, the relative risk, expressed as toluene equivalent, was determined by multiplying the risk potential per unit release obtained from the risk assessment tool by the environmental release.

### 5.1 Life cycle inventory methodology

**Production and manufacturing stages** The EIO-LCA was used to obtain the total environmental releases of DecaBDE and 55 additional chemicals and the total industrial output (in US\$) from the production and manufacturing stages. The EIO-LCA model is widely used, easy to access for rapid analysis, and allows users to estimate the overall resource use and chemical releases from producing specific commodities or services over the entire supply chain, based on economic activity (CMU Green Design Institute 2006). For example, energy use, the amount of air pollutants, hazardous wastes, and toxics released can be obtained from the EIO-LCA model based on a certain dollar amount of producing a commodity or service.

In the production stage, the reaction pathway of DecaBDE was determined and the reactants and intermediate products



**Fig. 2** Schematic illustration of the methodology used to integrate an environmental fate and transport model (CHEMGL), an economic input–output life cycle assessment (EIO-LCA) model, and a risk assessment tool for a screening-level analysis. The CHEMGL is used to estimate chemical concentrations that are input into the Risk

Assessment Tool to calculate a risk potential per unit release. The EIO-LCA model is consulted to obtain environmental releases from the production and manufacturing life cycle stages for relative risk calculation

**Table 2** Manufacturing Stage: five electronic and five textile products and economic sectors identified in the EIO-LCA for the LCA case study

Product(s)	Source	Sector
Flame retardant material	Posner 2004	Alumina refining
Plastics resins	Janssen 2005	Custom compounding of purchased resins
Laminated plastics	Janssen 2005	Laminated plastics plate, sheet, and shapes
TV housings	Janssen 2005	Plastics plumbing fixtures and all other plastics products
Plastics	Janssen 2005	Plastics material and resin mfg
Dyes and pigments	Janssen 2005	Synthetic dye and pigment manufacturing
Bedspreads, curtains	Cahill et al. 2005	Knit fabric mills
Textiles (fire finishing)	Janssen 2005	Textiles and fabric finishing mills
Drapes	Cahill et al. 2005	Broadwoven fabric mills
Mattresses	Cahill et al. 2005	Other rubber product manufacturing

involved in the formation of DecaBDE were verified. Phenol is converted to diphenyl ether, an intermediate product, via the Williamson ether synthesis and, then, is brominated using a catalyst and excess bromine to produce DecaBDE (Kirk-Othmer 2005). In the EIO-LCA model, it was determined that fire retardant chemical preparations are manufactured under the “other miscellaneous chemical product manufacturing” sector. The total industry output (US\$) for this sector was obtained from the EIO-LCA, and this value of economic activity was input into the EIO-LCA to estimate the release of phenol, bromine, and decabromodiphenyl ether. The relative risks from diphenyl ether were not assessed because this chemical is an intermediate product that is assumed to be completely converted in the production of DecaBDE.

For the manufacturing stage, DecaBDE is primarily used in electronic and upholstery textile products that were identified from the literature (Table 2). In the EIO-LCA model, the sector descriptions were used to select key sectors in the manufacturing stage that included the products identified from the literature—five electronic related sectors

and five textile related sectors (see Table 2). The industry output (US\$) and chemical releases of the ten sectors were estimated using the EIO-LCA. Several sectors were not included in the LCA because they accounted for a small fraction (less than 1%) of the overall releases of DecaBDE.

**Consumption stage** For the consumption stage, the emission rate of DecaBDE from products in service was estimated using a method developed by the Danish EPA. As required for this method, the accumulated amount of DecaBDE in the US and the global market distribution of DecaBDE were determined from the literature. To calculate the total emission of DecaBDE from products in service, it was assumed that the accumulated amount of DecaBDE in 2001 represented 10 years of consumption (approximately 24,000 tons). The distribution of DecaBDE was estimated from the global market demand of BFRs at 27% (BSEF 2001). An emission factor of 0.04% DecaBDE emitted per year and an error factor of 10 were applied to estimate the total emission of DecaBDE from products in service (Lassen et al. 1999). Both of these factors were adapted

**Table 3** EIO-LCA estimations of total industry output and chemical releases from products and economic sectors in DecaBDE production and manufacturing stages

Life cycle stage	Sector(s)	Product(s)	Total industry output (\$ millions)	Total chemical released (kg) <sup>a</sup>			Total chemical released from sector(s) (kg)
				Air	Land	Water	
Production	Other miscellaneous chemical product manufacturing	DecaBDE production	11,796	8,160.8	34,406.4	0.0	42,567.2
		Phenol		39,739.3	0.3	45.0	39,784.6
		Bromine		12,422.2	2,920.5	0.0	15,342.7
Manufacturing	Electronic	Flame retardant material, plastic resins, laminated plastics, TV housing, etc	122,785	14,529.8	49,673.2	15.0	64,217.9
	Textile	Dyes and pigments, bedspreads, drapes, mattresses, etc.	57,861	10,306.1	60,339.5	4,380.1	75,025.8

<sup>a</sup> The production stage includes releases from DecaBDE, phenol, and bromine. The manufacturing stage lists releases only from DecaBDE



**Table 4** Manufacturing stage: top three economic sectors that represented the greatest relative risk to humans and fish

Risk category	Sector	Total relative risk <sup>a</sup>	Overall relative risk from exposure pathway <sup>a</sup>
Humans via inhalation	Knit fabric mills	2e+10	4e+10
	Textile and fabric finishing mills	1e+10	
	Custom compounding of purchased resins	9e+09	
Humans via ingestion	Plastics material and resin manufacturing	8e+10	2e+11
	Custom compounding of purchased resins	3e+10	
	Textile and fabric finishing mills	3e+10	
Fish	Plastics material and resin manufacturing	4e+08	6e+08
	Plastics plumbing fixtures and all other plastics	7e+07	
	Other rubber product manufacturing	5e+07	

<sup>a</sup> Expressed as kilograms of toluene equivalence

from the Danish EPA methodology. An error factor was applied due to the assumptions made in the estimation technique.

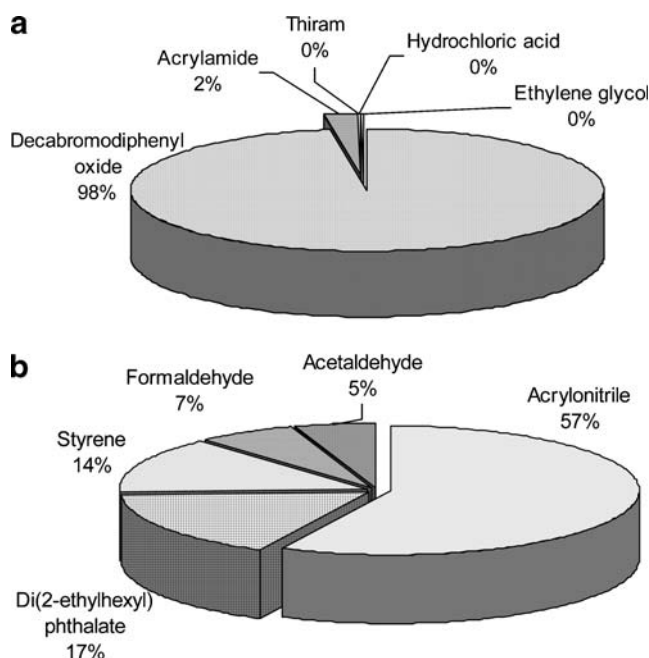
## 5.2 Life cycle impact assessment methodology

The main difficulty of performing an LCA on emerging chemicals of concern is the limited information available. The necessary physical–chemical input data for CHEMGL were obtained from databases (Kline et al. 2000; ChemOffice 2000; US NLM 2005) and handbooks (Howard 1991; Mackay et al. 1992) or estimated using the US EPA EPI Suite (US EPA 2000) based on chemical structure. The required properties include—half-life of each chemical in air, water, aerobic and anaerobic environment, Henry's law constant, octanol–water partition coefficient, molecular weight, melting point, vapor pressure, and diffusivity in both air and water. The reaction rate constant of a chemical in each compartment in CHEMGL was determined based on the chemical's half-life by assuming a first order reaction. The chemical concentration in each environmental compartment was estimated from CHEMGL for the production, manufacturing, and consumption stages. Combined with chemical concentrations, data on exposure factors—the rate at which humans exposed to a chemical in a specific compartment (US EPA 1997), lethal concentration 50 (LC50; US EPA 2000), reference dose (RAIS 2005), and the threshold limit value (ACGIH 2000) were input to the risk assessment tool. All chemicals, physical–chemical properties, environmental concentrations and releases, and toxicity values can be found in Wright (2007).

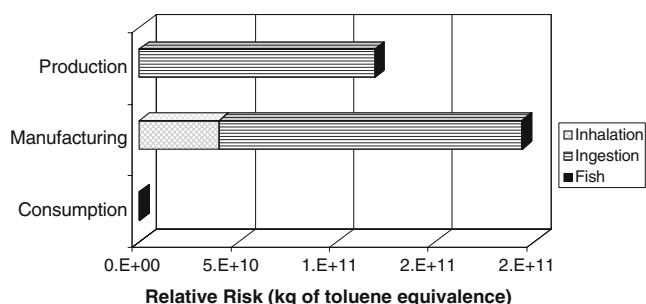
During the production and manufacturing stages, other chemicals in addition to DecaBDE are utilized in the production of DecaBDE (e.g., bromine and phenol) and in the manufacturing of electronic and textile products. Using the EIO-LCA model, 55 additional chemicals were identified from the production and manufacturing sectors based

on the mass of each chemical emitted from those sectors (Wright 2007). The risk from these 55 chemicals was evaluated to compare with DecaBDE.

The chemical concentrations from the production and manufacturing stages were estimated in the CHEMGL model for the ten compartments based on a unit release in the following compartments: air boundary layer, surface water, surface soil, and ground water. The chemical concentration for biota phase in surface water was also estimated to determine the concentration in fish. The concentration values were input into the risk assessment tool to calculate the risk potential to humans and fish per unit release for each chemical. The risk to humans was assessed via two exposure pathways: inhalation and ingestion of water, fish, soil, and vegetables. The risk to fish was calculated based on chemical concentration in



**Fig. 3** Top five chemicals (of the 56 chemicals evaluated in the study) that resulted in the greatest relative risk to **a** humans and **b** fish



**Fig. 4** Comparison of the total relative risk for each risk category and the overall relative risk posed by each life cycle stage

surface water and LC50. The risk potential per unit release was, then, multiplied by the environmental release estimated from the EIO-LCA model to determine the relative risk of each chemical. The total relative risk for each exposure pathway in each sector was calculated by adding the relative risks of all chemicals in that sector. The overall relative risk for each exposure pathway was calculated by adding the total relative risks of the ten sectors.

The relative risk for DecaBDE in the consumption stage was calculated using a similar procedure as the production stage; however, the environmental releases were estimated using the Danish EPA methodology instead of the EIO-LCA model.

## 6 Life cycle inventory

### 6.1 Production and manufacturing stages

The results of the EIO-LCA model outputs for the production and manufacturing stages are shown in Table 3. Based on the total releases obtained for the production stage, decabromodiphenyl ether and phenol are released in quantities two and half to three times greater than bromine. The majority of DecaBDE releases from the manufacturing stage came from textile related products, primarily from the

manufacturing of dyes and pigments, bedspreads and curtains, and fire finishing textiles. The manufacturing of flame retardant material, plastic resins, and laminated plastics resulted in the main contributions of releases from electronic related products.

### 6.2 Consumption stage

Using the methodology developed by the Danish EPA, the emission rate of DecaBDE in the US was estimated to be 2.6 tons/year. Using an error factor in this calculation resulted in a reduced emission rate of DecaBDE (by a factor of 10); however, the overall relative risk of the consumption stage was not significantly affected relative to the production and manufacturing life cycle stages.

## 7 Life cycle impact assessment

In this section, the risk assessment tool is utilized to evaluate the environmental concentrations determined from CHEMGL and to calculate the relative risk (expressed as kilograms of toluene equivalence) for each chemical and sector in the life cycle stages.

For the production stage, the relative risk was determined for DecaBDE, phenol, and bromine. DecaBDE posed the greatest relative risk to humans through ingestion. Overall, DecaBDE represents the greatest relative risk for the production stage by five and six orders of magnitude over bromine and phenol, respectively.

The relative risk for the manufacturing stage was determined for the ten sectors. The top three sectors that represent the greatest total relative risk to humans and fish are shown in Table 4. For humans and fish, the risk is high. For example, the risk to humans via inhalation from 1 kg of chemicals in the knit fabric mills sector represents  $2.0 \times 10^{10}$  kg toluene equivalence.

The top five chemicals were evaluated from the production and manufacturing stages to determine which

**Table 5** Comparison of the risk per unit release posed by the potential DecaBDE breakdown PBDE congeners (Hepta-, Hexa-, Octa-, and NonaBDE)

PBDE congener	Total risk/unit release <sup>a</sup>			Overall risk/unit release <sup>a</sup>
	Inhalation	Ingestion	Fish	
Nonabromodiphenyl Oxide	1e+01	—	6e+09	6e+09
Octabromodiphenyl Oxide	1e+01	5e+09	2e+04	5e+09
Heptabromodiphenyl Oxide	1e+01	—	1e+08	1e+08
Hexabromodiphenyl Oxide	1e+01	—	2e+07	2e+07
Decabromodiphenyl Oxide	1e+01	2e+07	4e+00	2e+07

<sup>a</sup> Expressed as kilograms of toluene equivalence

of the 56 chemicals resulted in the overall greatest relative risk to humans and fish. As shown in Fig. 3a, DecaBDE represents approximately 98% of the total risk to human health; however, DecaBDE does not represent a significant risk to fish (Fig. 3b).

In the consumption stage, DecaBDE represents the greatest risk to humans from ingestion by seven orders of magnitude over the risk to humans via inhalation. However, the risk to fish is seven orders of magnitude smaller than the risk to humans (Wright 2007).

The manufacturing and production stages represent the greatest overall risk to humans, 62% and 38%, respectively (Fig. 4). Ingestion represents the greatest risk to humans for the production, manufacturing, and consumption stages. The manufacturing stage represents virtually all of the risk to fish.

As shown in Table 5, the risk per unit release from four DecaBDE breakdown products was assessed for each risk category. Values for the reference dose are currently unavailable for Hepta-, Hexa-, and NonaBDE; therefore, the risk per unit release to humans through ingestion can only be assessed for OctaBDE, which is greater by two orders of magnitude over DecaBDE. The risk per unit release posed from inhalation was similar for the four lower PBDE congeners but less than one order of magnitude greater than DecaBDE. LC50 values were available in the literature for OctaBDE and DecaBDE; however, the remaining PBDE congeners LC50 values were estimated using EPI Suite. Based on the estimated LC50 and missing reference dose values, DecaBDE represents the least amount of risk per unit release by one to two orders of magnitude.

## 8 Conclusions

The study demonstrates that the approach of integrating EIO-LCA with risk assessment is suitable for screening-level analysis. It is relatively easy to compile life cycle inventory data compared with traditional LCA. It provides meaningful results to understand the fate and transport of the chemicals examined and can identify the critical life cycle stage and specific chemicals with high relative risks. The analysis from this study clearly indicates that the manufacturing and production stages represent the greatest risk to human health and fish.

- (1) *DecaBDE*. The manufacturing and production life cycle stages have the highest DecaBDE releases by more than three orders of magnitude over the consumption stage. Of the ten environmental compartments, the sediment compartment received the highest DecaBDE concentration for the production, manufacturing, and consumption stages. Comparing the total

relative risk of releases from only DecaBDE, the production stage has the highest relative risk by less than one order of magnitude over the manufacturing stage and three orders of magnitude over the consumption stages.

- (2) *Additional Chemicals*. The results from the 56 chemical releases are similar to the DecaBDE only releases for the total relative risk. The manufacturing and production stages have the highest relative risk, both of which are greater than the consumption stage by three orders of magnitude.

## 9 Recommendations

- (1) *Potential improvement in the life of DecaBDE*. As mentioned above, the manufacturing and production stages represent the greatest risk. This offers the greatest opportunities for reducing risks to human health and fish. These two stages allow for easier industry control and government regulation because there are fewer sources than in the consumption stage. For example, the textile and fabric finishing mills sector poses high relative risk to humans through both inhalation and ingestion exposure pathways. If chemical releases from this sector are controlled more effectively, the overall risk may be lowered. Additionally, for the production, manufacturing, and consumption stages, the ingestion exposure pathway poses the greatest risk to humans that can be controlled and reduced through various safety precautions in the workplace.
- (2) *Application of the methodology*. This integrated life cycle methodology allows chemical designers to evaluate each stage and assess areas where the risk can be minimized through the use of alternative chemicals or process operations. From the results of this study, other chemicals that pose significant risk (e.g., formaldehyde acrylamide, styrene) can be avoided or their quantities reduced and the potential risks posed by breakdown products (e.g., HexaBDE, HeptaBDE, OctaBDE, NonaBDE) can be analyzed. This allows policy makers to use these results to formulate policies that protect workers and consumers from these risks.

**Acknowledgment** The authors gratefully acknowledge support to Ms. Wright from the National Sciences Foundation through the Research Experiences for Undergraduates program (Grant No. EEC 0453174) and the Integrative Graduate Education, Research, and Training program (Grant No. DGE 0333401).



## References

- American Conference of Governmental Industrial Hygienists (ACGIH) (2000) TLVs and BEIs threshold limit values for chemical substances and physical agents and biological exposure indices. ACGIH, Cincinnati
- Bilec M, Ries R, Matthews HS, Sharrard AL (2006) Example of a hybrid life cycle assessment of construction processes. *J Infrastruct Syst* 12:207–215
- Brominated Flame Retardant Industry Panel (BFRIP) (2002) Voluntary Children's Chemical Evaluation Program (VCCP) Data Summary: Decabromodiphenyl ether. American Chemistry Council, Arlington
- Brominated Science and Environmental Forum (BSEF) (2001) Major brominated flame retardants volume estimates: Total market demand by region. BSEF, Brussels, [http://www.bsef.com/docs/BFR\\_vols\\_2001.doc](http://www.bsef.com/docs/BFR_vols_2001.doc)
- Butt CM, Diamond ML, Truong J, Ikononou MG, Ter Schure AFH (2003) Spatial distribution of polybrominated diphenyl ethers in southern Ontario as measured in indoor and outdoor window organic films. *Environ Sci Technol* 38:724–731
- Cahill R, Summerton L, Clark J (2005) Green chemistry and the producer: flame retardants. University of York, York, pp 1–91
- CambridgeSoft Corporation (2000) ChemOffice—ChemDraw Ultra (Chemical structure drawing standard) Version 6.0. CambridgeSoft Corporation, Cambridge
- Carnegie Mellon University (CMU) Green Design Institute (2006) Economic input-output life cycle assessment (EIO-LCA) model. CMU, Pittsburgh, <http://www.eiolca.net/>
- Chen H, Barna BA, Rogers TN, Shonnard DR (2001) A screening methodology for improved solvent selection using economic and environmental assessments. *Clean Prod Processes* 3:290–302
- Curran MA (1996) Environmental Life-Cycle Assessment. McGraw-Hill, New York
- Deanna JR, Fullerton AB (1994) Industrial Ecology: US–Japan Perspectives. National Academy, Washington, D.C.
- Gerecke AC, Hartmann PC, Heeb NV, Giger W, Schmid P, Zennegg M, Kohler M (2005) Anaerobic degradation of decabromodiphenyl ether. *Environ Sci Technol* 39:1078–1083
- Guinée J, Heijungs R (1993) A proposal for the classification of toxic substances within the framework of life cycle assessment of products. *Chemosphere* 26(10):1925–1944
- Hawkins T, Hendrickson C, Higgins C, Matthews HS, Suh S (2007) A mixed-unit input–output model for environmental life cycle assessment and material flow analysis. *Environ Sci Technol* 41:1024–1031
- Heritage Research Center (HRC), Ltd. (2004) The New PCBs? HRC, Missoula, <http://www.heritageresearch.com/pbde.htm>
- Hertwich EG, McKone TE, Pease WS (2000) A systematic uncertainty analysis of an evaluative fate and exposure model. *Risk Analysis* 20:439–454
- Hites RA (2004) Polybrominated diphenyl ethers in the environment and in people: A meta-analysis of concentrations. *Environ Sci Technol* 38:945–956
- Howard PH (1991) Handbook of Environmental Degradation Rates, 1st edn. Lewis, Chelsea
- Illinois EPA (2006) DecaBDE study: a review of available scientific research. A report to the general assembly and the governor in response to public act 94–100, 217/782–3397. Illinois EPA, Springfield
- Janssen S (2005) Brominated flame retardants: rising level of concern. Health Care Without Harm, Arlington
- Jolliet O, Rosenbaum R, Chapman PM, McKone T, Margni M, Scheringer M, Straalen N, Wania F (2006) Establishing a framework for life cycle toxicity assessment. Findings of the Lausanne Review Workshop. *Int J Life Cycle Assess* 11:209–212
- Kim YJ, Osako M, Sakai S (2006) Leaching characteristics of polybrominated diphenyl ethers (PBDEs) from flame-retardant plastics. *Chemosphere* 65:506–513
- Kirk-Othmer Encyclopedia of Chemical Technology (2005) Ethers, vol 10, 5th edn. Wiley, Hoboken, pp 567–583
- Kline AA, Rogers TN, Mullins ME, Dewan AK, Thomson GH, Willman TJ, Heward MS, Trumbell MR, Wells PM, Whitten CR, Zei DA, Donnellon EM (2000) Environ2001 version 1.0, EPCON International, Houston
- Larsen HF, Hauschild MZ (2007) Evaluation of ecotoxicity effect indicators for use in LCIA. *Int J Life Cycle Assess* 12:24–33
- Lassen C, Lokke S, Andersen LI (1999) Brominated flame retardants: substance flow analysis and assessment of alternatives, Environmental Project 494. Danish EPA, Copenhagen
- Mackay D, Shiu W, Ma K (1992) Illustrated handbook of physical–chemical properties and environmental fate for organic chemicals, vol 1–4, 1st edn. Lewis, Chelsea
- Matthews HS, Lave L, MacLean H (2002) Life cycle impact assessment: a challenge for risk analysts. *Risk Analysis* 22:853–860
- Osako M, Kim YJ, Sakai S (2004) Leaching of brominated flame retardants in leachate from landfills in Japan. *Chemosphere* 57:1571–1579
- Pant R, van Hoof G, Schowanek D, Feijtel TCJ, de Koning A, Hauschild M, Pennington DW, Olsen SI, Rosenbaum R (2004) Comparison between Three different LCIA methods for aquatic ecotoxicity and a product environmental risk assessment. *Int J Life Cycle Assess* 9:295–306
- Posner S (2004) Survey and technical assessment of alternatives to decabromodiphenyl ether (decaBDE) in textile applications. Swedish Chemicals Inspectorate, Sundbyberg, Order No. 510 792
- Risk Assessment Information System (RAIS) (2005) Toxicity and chemical-specific factors—nonradionuclides. RAIS, Oak Ridge, [http://risk.lsd.ornl.gov/cgi-bin/tox/TOX\\_select?select=nrad](http://risk.lsd.ornl.gov/cgi-bin/tox/TOX_select?select=nrad)
- Saouter E, van Hoof G, Pittinger CA, Feijtel TCJ (2001) The effect of compact formulations on the environmental profile of northern European granular laundry detergents, Part I: Environmental risk assessment. *Int J Life Cycle Assess* 6:363–372
- Saouter E, van Hoof G, Feijtel TCJ, Owens W (2002) The Effect of compact formulations on the environmental profile of northern European granular laundry detergents, Part II: Life cycle assessment. *Int J Life Cycle Assess* 7:27–38
- Swarr TE, Cline HJ, Jeong S, Dickinson DA, Caudill RJ (2004) Evaluating supply line sustainability and business environmental risk. IEEE Electronics and the Environment, New York, pp 264–269
- US EPA (1997) Exposure Factors Handbook Revised. US EPA, Washington, D.C.
- US EPA (2000) EPI Suite version 3.12, US EPA version for Windows. US EPA, Washington, D.C.
- US National Library of Medicine (US NLM) (2005) Toxicology data network (TOXNET)—hazardous substances data bank. US NLM, Bethesda, <http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB>
- Wright HE (2007) Integrating life cycle assessment and relative risk for an emerging chemical of concern: the flame retardant, decabromodiphenyl ether or oxide (DecaBDE), MS Thesis. Michigan Technological University, Houghton
- Zhang Q, Crittenden JC, Shonnard D, Mihelcic JR (2003) Development and evaluation of an environmental multimedia fate model CHEMGL for the Great Lakes region. *Chemosphere* 50:1377–1397
- Zhu LY, Hites RA (2005) Brominated flame retardants in sediment cores from Lakes Michigan and Erie. *Environ Sci Technol* 39:3488–3494